WL-TR-94-5045

HIGH RESOLUTION, LARGE SCALE MEASUREMENT PROCESSES

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July 1994
Final Report for Period May 1991 through Jun 1993

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NOTICE

This technical report has been reviewed and is approved for publication.

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	Jul 1994	Final 05/01/91--06/30/93

4. TITLE AND SUBTITLE

HIGH RESOLUTION, LARGE SCALE MEASUREMENT PROCESSES

5. FUNDING NUMBERS

PE: 61101F
PR: 0100
TA: EL
WU: 13

6. AUTHOR(S)

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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

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Wright Laboratory (ASC)
Air Force Materiel Command
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8. PERFORMING ORGANIZATION REPORT NUMBER

WL-TR-94-5045

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Solid State Electronics Directorate
Wright Laboratory (ASC)
Air Force Materiel Command
Wright-Patterson AFB OH 45433-7331

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

This is an in-house ILIR research report

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

As spatial resolution of any measurement process increases, the amount of data per unit area (or volume) increases, leading to huge amounts of data and/or long measurement times when attempting to map small spatial variations in material properties over large spatial dimensions. It is therefore desirable to develop techniques in which high resolution information can be obtained, while maintaining the ability to cover large areas without being overwhelmed by measurement time or data. This report discusses the issues involved and seeks to formulate and advocate strategies that could guide such endeavors.

14. SUBJECT TERMS	15. NUMBER OF PAGES
Metrology, high resolution spatial measurements, high density spatial measurements	34
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UNLIMITED

TABLE OF CONTENTS

FOREWORD

This is the final report for the in-house work unit 0100EL13 in the Electro-Optic Techniques and Applications Branch of the Electro-Optics Division, Solid State Electronics Directorate, entitled, for lack of a better name, *Macroscopic Techniques for Inferring Microscopic Properties*. This work unit was funded with Laboratory Director's Funds and covered the period 1 May 91 through 30 Jun 93. Jeff L. Brown was the work unit monitor and principal investigator.

The original concept behind this work unit was to develop a few specific methods of measuring average microscopic properties over large sample surfaces by using large field-of-view (FOV), macroscopic measurement techniques to speed up the process. This involved attempts to use microscopic resolution instruments to "calibrate" large FOV instruments. One such microscopic (actually nanoscopic) resolution instrument was the newly available scanning probe microscope; but since the scanning probe microscope is capable of extremely high resolution and correspondingly small fields-of-view, it served to amplify the pressing problem that there is a serious tradeoff between high resolution and large sample measurement because of the rapid increase of data and measurement time per unit area as resolution increases.

So the work turned to a methodical examination and formulation of measurement processes to address this problem, guided by the author's experience in several metrology problems involving microscopic resolution. After a careful examination of several current measurement techniques, and ever mindful of the increasingly desirable trend toward obtaining dense, full sample mapping of physical properties, this report took shape.

The author wishes to acknowledge the fruitful interactions with David Look, Dennis Walters, and Stu Cummins, Wright State University contractors in WL/ELO, Millard Mier, Rocky Sherriff, and others in WL/ELR, Susan Hastings and Paul Jero of WL/MLLM, and Rich Fletcher and Rand Biggers of WL/MLPO. These interactions highlighted many of the issues discussed in this report and emphasized the need for a generalized approach to high resolution, large scale measurement processes.

1.0 INTRODUCTION

The general objective of this work was to explore ways to measure properties of materials over large sample areas (or volumes) where the properties vary on a spatial scale many orders of magnitude smaller than the sample dimensions. For example, it is currently possible to measure the roughness of a surface with a lateral resolution of one nanometer or better; while, at the same time, it may be desirable to measure this roughness over a surface area as large as 1000 cm^2. The task of making such a measurement is monumental in that there are 10^{10} nm^2 in an area of 1000 cm^2. If 1 nm^2 is the area resolution element, and if the measurement can proceed even at 1000 resolution elements per second, it would still take about 4 months to measure the entire surface. Generally speaking, this is unacceptable in terms of the cost of obtaining the desired information.

The problem just stated is a natural result of man's ability to observe physical phenomena with ever increasing detail. As spatial resolution of any measurement process increases, the amount of data per unit area (or volume) increases. The usual result is to decrease the total space measured so as not to become overwhelmed by time or data or both.

Virtually all techniques employed to measure material properties are progressing toward higher and higher spatial resolution. Much is learned about the microscopic nature of materials as a result of this progression, but what is usually lost in the process, and largely overlooked, is spatial uniformity.

It is therefore desirable to develop techniques in which high resolution information can be obtained, while maintaining the ability to cover large areas without being overwhelmed by measurement time or data. This report discusses the issues involved and seeks to formulate and advocate strategies that could guide such endeavors.

Throughout this report, it should be noted that while the discussion primarily refers to the measurement of physical properties as a function of area, the same arguments hold, in general, for the measurement of physical properties as a function of volume, or for that matter, as a function of a single spatial coordinate. In addition, the reader may find the author's working definitions of terms used in this report in the Glossary at the end of this report.

In the next section, some further background on the issue just introduced is given. In Section 3, the foundation of some measurement strategies is spelled out. Section 4 is a discussion of some of the metrology issues which presented themselves as a result of the author's involvement in whole wafer material characterization relating to electronic materials. The remainder of this report contains some conclusions, recommendations, and a glossary of terms.

2.0 BACKGROUND

As our technology has advanced, it has become more and more apparent that there is much to learn about the microscopic nature of materials and physical phenomena. There is hardly an area in the physical sciences where this is not the case. With a basic understanding of this microscopic nature, the ability to create new materials and devices, and to harness quantum phenomena, becomes possible.

Measurement techniques have generally kept pace with the need for increased scrutiny of microscopic properties through gradual increases in spatial resolution. What has not kept pace, however, is the ability to examine large total areas while maintaining some semblance of microscopic resolution in order to evaluate spatial uniformity or to map properties over relatively large areas.

An illustration of this can be found in microelectronics manufacturing. The trend has always been a decrease in device dimensions while, at the same time, substrate sizes have increased to achieve greater yield, performance, and economy of scale. As devices shrink in size and as their performance depends more and more on microscopic properties of the materials they are made from, measurements of these properties become more important. The measurement of microscopic properties requires high resolution, but large substrates invariably contain nonuniformities in their microscopic properties which can require measurement over the entire substrate in order to track yield and performance variations that are material related. Furthermore, process nonuniformities can occur on a spatial scale which is also small compared to the size of the substrate.

The current state-of-the-art relies heavily on what amounts to spot checking. Measurement devices with high resolution capability are employed to study microscopic properties in detail, but in general they are not designed to study microscopic properties over large areas. Rather, they can supply the user with detailed information about a particular area provided the user has some *a priori* reason to concentrate on that particular area. Frequently, the user simply employs a quasi-random survey of several spots on a large sample.

This survey approach to material analysis has served well for a great variety of applications, but it often becomes little more than a qualitative picture of the sample under study if one finds wide variations in the measured property as a function of area. One can attempt to set upper and lower bounds on the measured property, but little else without long and tedious measurement of many spots. Furthermore, it is not wise, in general, to assume homogeneity or linear variation of a material property based on a few widely spaced measurements. Only a sufficiently dense map can supply that information, but a methodology must be in place which will assist in determining what constitutes "sufficiently dense."

In addition, few, if any, material properties are continuous on every spatial scale. At some size scale, a property may become discrete or quantized. Knowledge of how a property varies with scale, and the scale, if any, at which the property becomes discrete is not only a useful quantification of the property, but it can assist in defining or bounding the measurement process; that is, it can determine what constitutes a sufficiently dense measurement, for example. This in turn may determine the most efficient measurement scheme. This discussion will continue in Section 4.

Consider now the problem of counting microscopic particles on a flat, smooth surface. This can be done quite rapidly with state-of-the-art surface particle counters using laser light scattering. They work on the principle that a particle will scatter more light than the surface roughness. The technique detects the presence of one or more scatterers under the laser beam and can attempt to assign a size based on the measured and calibrated scattering cross section. What cannot be determined easily is the difference between one large particle and two or more smaller ones within the area of the beam spot if the scattering cross section is similar. The best solution is to increase the spatial (lateral) resolution, but in a way that doesn't sacrifice the relatively short measurement time that currently exists.

Reasonable measurement times often dictate using macroscopic, low spatial resolution techniques with relatively large pixel sizes for mapping surface properties across an entire sample. It should be possible, however, for these techniques to quantify average microscopic properties for each pixel if calibrated with microscopic, high spatial resolution measurements. The payoff of this approach to measurement would be the ability to infer microscopic properties over comparatively large areas without the enormous amounts of time it would take to map a large surface entirely with a high resolution technique.

Some techniques already employ such a scheme. Whole wafer etch pit density mapping employs a manual count of microscopic etch pits at several sites to calibrate an infrared transmission measurement where the transmission is proportional to the number of etch pits in the field-of-view.[1] Sufficient calibration sights allow the transmission measurements to be converted to etch pit densities, and the transmission measurement can proceed at a much faster rate than manual counting with a microscope.

Increasing speed and accuracy of microscopic counting is one solution to large sample mapping, but this is often difficult. An example where this has been somewhat successful is a technique called spatially resolved photoluminescence (SRPL).[2] It can detect dislocation defects in semiconductor materials by achieving high spatial resolution photoluminescence contrast between dislocations and surrounding material. This technique has 1-μm resolution at video frame rates where the frame size is several hundred micrometers on a side, but still suffers from a real time data reduction problem. In other words, it can achieve high spatial resolution at a high data rate, but the data cannot be quickly reduced to a useful form, such as the number of dislocations per frame.

With the increasingly widespread use of scanning probe instruments, the problem is only likely to get worse. These instruments can attain subnanometer spatial resolution with valuable information in each measurement area. It is currently impossible to use such high resolution instruments to map large areas.

It is arguable whether advances in measurement techniques drive applications or applications drive advances in techniques. If a measurement technique gains even a small incremental increase in resolution, applications for the measurement will invariably spring up. On the other hand, practically any endeavor requiring measurement can benefit from increased resolution, and this provides impetus for achieving higher resolution. However, when the increase in resolution is spatial as opposed to magnitude, serious consideration must be given to the tradeoff between what is gained by the increase in resolution and what is lost in the form of knowledge of longer range variations.

In the next section, some methodologies for approaching the problem of measuring microscopic properties over large areas are presented.

3.0 MEASUREMENT STRATEGIES

To set up the problem, imagine a surface of area **A** whose temperature **T** varies as a function of **x** and **y** in some unknown fashion. A map of the surface temperature is desired such that any nonuniformities, gradients, or hot spots can be detected and visualized. Suppose that a thermal imager is employed to measure the function **T(x,y)**. Suppose also that the thermal imager has a variable field-of-view **F**, defined as the surface area that can be imaged in one frame of data, and a detector with **N** by **N** pixels, and that integration time for the detector is independent of **F**. In this case, the time t_f required to measure one frame, the N^2 pixels of the thermal image within **F**, is the same regardless of **F**.

The total measurement time **t** for the sample, then, is

$$t=t_f A/F$$

where **A/F** is the number of frames required to map the sample. The number of data points **M** acquired for the map is

$$M=N^2 A/F$$

The resolution **R**, in terms of the surface area imaged onto each pixel of the detector, is

$$R=F/N^2$$

It is clear from these simple expressions that in order for resolution to improve (**R** decrease), **F** must decrease; and since **t** and **M** are inversely proportional to **F**, total sample measurement time and total data increase linearly as area resolution improves.

It should be noted here that the above expression for resolution does not mean to imply that resolution is a function of only field-of-view (frame size) and the number of pixels per frame. There are fundamental physical constraints, such as the resolution of light in ordinary optical systems, which pose other limits on resolution, but the expressions above are general and applicable to most measurements taken as a function of area.

The basic question then is the following: how does one map a material property of a sample when the material property varies on a scale many orders of magnitude smaller than the sample dimensions? In other words, suppose that in the example above, the temperature **T(x,y)** is desired with an area resolution near the resolution limit of light which is of the order of 1 μm^2. If the sample area is 1 cm^2, then the data set would consist of at least 10^8 data points. A computer file to store this data would contain at least as many bytes, or 100 MBytes. While acquisition time for this amount of data may be reasonable (less than an hour), manipulating and displaying 100 MBytes of data per square centimeter is not feasible. Furthermore, 1 cm^2 is not a particularly large sample for an application of microthermal imaging analysis.

In order to measure properties of materials over large sample areas while maintaining high spatial resolution, four methods are presented. These methods are described here as direct, indirect, random sampling, and deterministic sampling.

3.1 Direct Method

This is the method just described in the thermal imaging example above. High resolution measurements are made over the instrument field-of-view, multiple frames are acquired by translating the sample or the instrument field-of-view, and then the frames are pieced together to form a spatial map of the measured property. Two things are likely to result from this endeavor: a large amount of time spent making the map and a large amount of data accumulated.

This method is by far the most widely used for obtaining a dense map of a physical property regardless of the scale of interest. It is the simplest to implement when **t** and **M**, as defined above, are reasonable, and **R** is sufficient. It also is the method most limited by resolution **R**, with data sets and measurement time quickly becoming intractable as **R** decreases. Relief from this situation can be obtained by modifying the direct method as follows.

3.2 Indirect Method

In this method, two or more techniques are combined to improve measurement efficiency when compared to the direct method. This can take several forms. One such form involves a combination of two techniques, the first of which employs a high resolution instrument that obtains its resolution over a field-of-view approximately the same size as an individual pixel of the second instrument. The second instrument averages the property of interest over the pixel, reducing the data to a single value for each pixel.

The high resolution instrument effectively calibrates the low resolution instrument and can be employed to monitor the correlation. In this case, the high resolution instrument is used just enough to maintain the desired level of accuracy. The total data set is reduced and the measurement time is driven by the speed of the low resolution instrument and the number of frames measured by the high resolution instrument.

This method is particularly useful for counting small objects or defects when the quantity measured by the low resolution technique is proportional to the number of objects in the field-of-view. Still, the proportionality needs to be determined experimentally to account for intersample or intrasample variations. This is the method employed in whole wafer etch pit density mapping alluded to previously.

The process of correlating the high resolution data and the single pixel value from the low resolution measurement for the same sample area produces what is often called a training set. For the case of counting defects, a particular number of defects produces a certain response in the low resolution instrument. This response is correlated with the number of defects in the pixel as measured by the high resolution instrument. Registration is key. The precise area covered by the low resolution pixel must be the only area measured by the high resolution technique. This is often a weak point of the indirect method.

Rather than a simple proportionality between low and high resolution measurements, the training set provides a parametric fit between the two. This takes into account complex relationships between the low and high resolution measurement and may even work in the presence of high instrument noise, background properties not of current interest to the measurement, and unknown properties that the instruments are sensitive to. Of course the more complex the correlation, the greater the requirement is for more data in the training set. A sufficiently robust training set can produce accurate measurement correlations across an entire sample. If many samples are included in the training set, it can be used for different samples.

In its most common form, a combination of two techniques usually exists on two separate platforms thus making it difficult to go between the two without highly precise and automated equipment. Lacking such equipment, the user is required to choose the locations for high resolution measurement without benefit of knowing the full range of response of the low resolution measurement for a given sample. As a result, the training set is quite often limited in that it doesn't sample the full range of variations across a sample or among different samples. Without the ability to easily move the sample between the two instruments, the correlation cannot be monitored on a continuous basis and measurement accuracy decreases if the variations exceed the range of the training set. The correlation is only as good as the training set.

This difficulty can be alleviated by the ability to easily move the sample between the two instruments with precise registration. The high resolution instrument can then monitor the correlation and continuously update the training set or flag situations in which the correlation falls outside set parameters. Another way of obtaining a more robust training set is to employ random sampling in obtaining the training set. This way, the training set is more likely to contain areas representative of the entire range of the measured properties.

The response of the low resolution technique may be influenced by two microscopic properties at the same time. In this case, the low resolution technique must have an additional degree of freedom in order to accurately distinguish the two properties. Using again the example of the infrared transmission technique in whole wafer etch pit density mapping, two wavelengths could separate the two properties and the training set would be assembled by training on the two microscopic properties. Each additional property of interest that can be measured by the high resolution technique requires an additional degree of freedom in the low resolution technique in order to be separately measured.

If additional degrees of freedom are not available to the low resolution technique, the high resolution technique may be useful in estimating the average value and uniformity of one or more properties thus allowing the low resolution technique to map the value of the property with the largest variation.

As previously stated, the indirect method may take several forms. It is not the purpose of this report to expound on the various forms, but one example would be a case where two different low resolution techniques are required to map separate effects as seen in the high resolution measurement. The two low resolution techniques may be on the same or different platforms, and may proceed simultaneously or separately if on the same platform. Other variations are possible.

3.3 Random Sampling Method

In this method, a single high resolution instrument is employed such that high resolution frames are chosen over the total sample area by any of a number of random sampling algorithms. Various computational techniques are then employed to draw conclusions about uniformity and to extrapolate between scan areas.

A prime advantage of this method is the overall reduction in total area measured, resulting in shorter overall measurement times and smaller data sets. Also, it has the advantage of being self-monitoring in that any conclusions drawn from extrapolation can be verified by measuring frames in the extrapolation zones. Furthermore, all measurement frames can be acquired at maximum resolution if desired.

The primary drawback to this method is that there is no way to know for certain what the properties of a particular area are unless that area is explicitly sampled in some way. This method also puts a heavy demand on data processing since each frame of data must be compared with other frames in successive iterations in order to make accurate extrapolations.

Very few instruments actually employ this technique, but it could be a cost effective way to modify existing high resolution instruments for large sample scanning.

3.4 Deterministic Sampling Method

This method is a direct extension of random sampling. While a variable field-of-view is not necessarily a characteristic of this method, it is instructive to allow this additional degree of freedom as illustrated below.

Consider an instrument with a variable field-of-view, fixed number of pixels per frame, and a sample translation system. A frame of data is acquired at the highest resolution near the center of the sample or some other appropriate starting point. Software makes note of any gradients, extrema, and spikes, and then acquires another frame immediately adjacent to the first frame. The process continues until enough data has been acquired to determine trends. For instance, if the frames are essentially featureless, the software then either increases the field-of-view (decreases the magnification), or skips one frame.

Each frame of data gives the software more information for determining the next course of action. It may be to continue to decrease the field-of-view or to skip more than one frame until an appropriate scan resolution is found. If a gradient or extrema is detected, the software can resume scanning adjacent frames or decrease the field-of-view. Sharp spikes or dips occurring in any frame might call for the instrument to search all adjacent frames for similar occurrences and to continue the high resolution mapping until these features disappear or until a trend can be established.

The courses of action taken by the software can be determined by specific parameters preset by the operator, by global search parameters, by artificial intelligence algorithms, or other suitable methods. Employing artificial intelligence would be analogous to automatically obtaining and continuously updating a training set.

Deterministic sampling should be superior to random sampling in a global sense. Without the decision making process used in deterministic sampling, random sampling may, in some instances, actually oversample a surface whose properties are highly uniform. In addition, deterministic sampling should obtain a more efficient increase in accuracy over random sampling. In other words, the accuracy of deterministic sampling does not necessarily improve with an increase in the number of frames sampled as it does in random sampling.

Although variable field-of-view is not necessarily a characteristic of deterministic sampling, this method makes good use of it. The ability to change field-of-view may involve complimentary techniques, as in the indirect method, or the same technique, as in the example here for deterministic sampling. Regardless of the method, changing field-of-view is a powerful way to optimize measurement efficiency. Even without a variable field-of-view, this method still has advantages over random sampling and could be the most efficient of all the methods described here for a wide variety of measurements.

The major drawback in the deterministic sampling method is the heavy requirement for sophisticated decision algorithms which have not, for the most part, been developed for such purposes. Development and implementation of such algorithms would not presumably be beyond the present state-of-the-art.

3.5 Issues Common to All Methods

Some measurement issues are common to all the methods described above. A few of these issues are discussed here.

A key part of the methods described above is automation. High data rates, large data sets, instrument control, and automated decision making are all inherent in these methods and in the problem at hand. It is often the case that one of these factors is reduced at the expense of another. For example, the indirect method may reduce data rate and volume over the direct method while requiring greater instrument control. The deterministic sampling method requires the greatest amount of automated decision making. The accuracy of the random sampling technique is directly related to the number of areas sampled and thus data rate and instrument control are most critical. Of course, the direct method might be the method of choice for any measurement if data acquisition rates, storage, and processing speeds were unlimited, and instrument control was simple. In other words, the degree to which a measurement can be automated often determines its capabilities and limitations.

Sample registration, as mentioned earlier, is another key issue. If the measurement process involves two or more instruments, or if the field-of-view is varied on a single instrument, registration will affect the accuracy of the measurement. This may seem too obvious to overlook, but the effect of poor registration is often greater than expected and the importance of registration is, in fact, often overlooked. Whenever the measurement relies on a correlation between two measurements, the accuracy will be a function of the degree to which the two measurements "see" the same area.

This entire discussion assumes that the information from any type of analysis can be presented in a meaningful way to human operators. This may require fast, sophisticated graphics, multimedia presentation, or other innovative methods, but not necessarily things that are beyond present day technology.

In the next section, some general metrology issues related to high resolution, large scale measurement processes are discussed.

4.0 DISCUSSION

High resolution, large scale measurement processes present some rather unique problems not encountered in other measurement processes. The following is a brief discussion of four such issues pointing out shortfalls and pitfalls in the current state-of-the-art and how they might be addressed.

4.1 Spatial Scale

At high enough resolution, many properties will become discreet. A good example of this occurs in defect counting. Many defects exist as highly localized variations in an otherwise homogeneous property. With a small enough frame size, it is possible to measure an area where there are no defects or where there is just a single defect.

This discreetness needs to be handled carefully. A common practice is to express surface defect densities in terms of a number per cm^2. If the frame size over which defects are counted is $5x10^{-4}$ cm^2, a typical frame size, then a quick calculation reveals that the "defect density" for a frame of this size containing a single defect is $2000/cm^2$. This number is of little use (except for comparisons to other measurements expressed in these units) especially if the next frame contains no defects ($0/cm^2$) or 2 defects ($4000/cm^2$). A better solution is to report the actual number of defects counted per frame and then specify the frame size.

When a technique such as visible light microscopy is used to count defects, as in the high resolution technique employing the indirect method, registration is critical to maintaining accuracy at low defect densities, i.e. high discreetness. A registration error of only a few percent can mean the difference between counting a single defect in the frame and zero defects in the frame. This leads to a poor correlation between the low and high resolution instruments and can be a source of very large errors in calculated defect densities.

4.2 Sufficiently Dense Measurements

Every time a measurement is made as a function of a spatial variable, the decision as to what constitutes a sufficiently dense measurement must be made. In making a profile or map of a physical property, the idea is to determine the variations in the property to the degree (resolution) that satisfies the requirement. This is often determined in an *ad hoc* fashion, and similar measurements may be carried out to satisfy similar requirements with rather different resolutions. Compounding this issue is the tendency to disregard resolution when making comparisons, or to neglect to report resolution along with the spatial property measured.

A specific example of this is the reporting of crystalline dislocation density for semiconductor wafers based on a half dozen counts over frames that are small compared to the wafer size. While this information can be useful in many respects, without knowing where the frames were counted, what the frame size was, how many frames were averaged, etc., valid comparisons are difficult. Different analysts can come to drastically different conclusions as to how many frames to count in order to specify the average dislocation density for a wafer.

Another example involves quantifying surface roughness. Even when lateral resolution is not an issue (that is, when the roughness measuring instrument can accurately resolve all features), the area over which the roughness is calculated makes all the difference in the outcome, and the reported value is next to meaningless without specifying the area.

Many of these difficulties could be remedied by appropriate standards. However, since standard practices typically lag behind the state-of-the-art of measurement capability, and since large scale, high resolution measurement processes are not, as yet, widely employed, standards are not likely to be written for many years. Thus, these difficulties will likely continue.

4.3 Parallel Measurement Channels

Most material surface analysis instruments obtain data through a single measurement channel. In fact, this author knows of no instrument that employs multiple channels in order to increase data acquisition. There are instruments, like the new atomic force microscopes, that acquire data over multiple channels in order to deduce lateral frictional forces acting on the probe. The result, however, is a single material property derived from data from multiple channels. It would certainly be desirable to have devices in which multiple frames of data, measuring the same material property, could be acquired simultaneously or nearly so.

If devices could be constructed in which multiple frames of data are acquired simultaneously, a major advancement could be made in high density measurement. These devices would consist of multiple probes (beams, physical probes, imaging apertures, etc.) with an individual signal processing channel for each probe. Yet, most of the hardware associated with translating and illuminating the sample, for instance, could be, and in most cases, should be the same. It is conceivable that each frame's data would have to be acquired, manipulated, reduced, and stored by an individual data processor, necessitating parallel processing or massively parallel computing.

Current technology may be on the verge of providing such devices. Mechanical and electrical device miniaturization will quite likely make parallel data channels a reality in the near future. Nonetheless, there are many hurdles to overcome that miniaturization alone cannot solve, such as the enormous date processing capability that would be required. Sophisticated algorithms would be required to shield an instrument user from data overload, and to reduce the data to meaningful terms.

4.4 Common Platforms

One of the apparent shortfalls in present day material measurement techniques is a lack of rather similar measurements existing on a common platform. For instance, room temperature photoluminescence, photoreflectance, and light scattering all employ one or more pump/probe beams, detectors, and in many cases, a sample translation system. It is conceivable that total system costs could be reduced by taking advantage of the fact that a single translation system, common beam path elements, and common detector elements could be shared by all techniques. Sophisticated optical and mechanical designs may also allow measurement channels to operate in parallel such that two or more of the above mentioned techniques could probe the sample at the same time.

This is only one of many conceivable examples of a common platform instrument. A reasonable approach would be to cluster similar measurement techniques into measurement modules where a single sample alignment and instrument setup would allow a user to perform multiple analyses on a sample.

As discussed in a previous section, a common platform instrument could solve many problems associated with registration errors when separate measurements are to be correlated. Sample registration should not be left to the limited ability of the human eye or other crude techniques if spatial correlations between different measurements are to be made on the same sample.

5.0 RECOMMENDATIONS

The following recommendations are an attempt to address some of the drawbacks of current measurement instruments and practices as presented throughout this report.

Instruments should be constructed which combine multiple techniques on a common platform. This could reduce sample registration problems, reduce instrument costs, and increase data acquisition efficiency. Alternatively, greater attention should be paid to sample registration when moving samples between different platforms. This could be accomplished through the use of common sample mounting modules which allow the sample to be transported between platforms without loss of registration. Such a mounting module holds the sample in a well defined orientation and position, and the orientation and origin position can be determined on any of the platforms through fiducial marks on the module.

Instruments should also be developed which employ parallel data channels. This could involve major developmental research, but it is not beyond the realm of present technology.

Standard practices should be developed ahead of, or at least in parallel with, new classes of instruments designed to overcome current limitations which are the subject of this report. Specifically, standard practices should be pursued which address 1) what constitutes a sufficiently dense measurement, 2) how to handle measurements involving low defect densities and other consequences of discreetness, and 3) how and when to specify field-of-view and resolution when reporting spatial measurements.

Deterministic sampling should be employed whenever practical by including it as an option on new instruments or by modifying old ones. Random sampling should be an option at the very least. The direct method should be employed whenever measurement size and data file size is tolerable and data can be reduced to a usable form. The indirect method should be combined with the use of common platforms and parallel data channels.

6.0 CONCLUSION

This report has presented some of the major issues involved in attempting to make large scale measurements with high resolution. In addition, some measurement strategies that could accomplish such tasks were introduced. While this report does not constitute a generalized approach, it is hoped that it may constitute a first step in that direction.

A great deal of effort in the Solid State Electronics Directorate has gone into developing and advocating high density, full wafer mapping of electronic materials which should pay off in the future. It is the author's opinion that this effort has positioned those involved in this work ahead of the game because a time will come when high density, full wafer mapping will be not just useful, but required in order to produce advanced devices which depend strongly on knowledge of microscopic features.

In order to stay ahead of the game, it would seem that a generalized approach to high resolution, large scale measurement processes should be pursued in anticipation of the time when such measurements will become more widespread and necessary to advance the technological state-of-the-art.

GLOSSARY

field-of-view - in optics, the area of the image plane that is actually imaged through an optical system; in general, the area that any area measuring device samples at a given time; see frame size.

frame size - a more generic term for field-of-view specifying the absolute or relative size of the sampled area in an area measuring instrument, usually containing several resolution elements; generically synonymous with sampling interval; see field-of-view.

intersample variations - variations among different samples.

intrasample variations - variations across a given sample.

magnitude resolution - the degree to which a physical property can be determined; scalar precision; see spatial resolution.

metrology - the science of measures and weights.

microscopic resolution - generally speaking, resolution beyond that of the unaided eye, requiring a microscope or other source of magnification; in particular, resolution on the order of 1 μm, i.e. being able to distinguish objects or features separated by a distance on the order of 1 μm.

resolution element - similar to the term pixel (picture element), it is the smallest distance, area, or volume element of a spatial map.

sample registration - placement of a sample on a measuring instrument such that the absolute or relative location on the sample at which measurements are taken is precisely known.

scanning probe microscope - a relatively new class of surface mapping instruments in which a fine probe tip is placed within nanometers of a surface and either the probe tip or the sample is translated in a raster scan in order to build up a surface representation one pixel at a time with spatial resolution to less than 1 nm.

spatial resolution - spatial precision; the physical size represented by the resolution element of a spatial map (other definitions are common); see magnitude resolution.

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